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Theoretical investigation of solar desalination with solar still having phase change material and connected to a solar collector

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ABSTRACT

A theoretical model is developed in this work to simulate a solar still connected to an external solar collector and incorporating Sodium Thiosulfate Pentahydrate as phase change material (PCM). Excellent agreement is obtained between the theoretical and experimental results for the unit productivity of fresh water and the basin water temperature profile. Sodium thiosulfate pentahydrate worked well as PCM to supply energy during night time for continuous water production and has improved the overall productivity. Incorporating large PCM mass in the system reduced the productivity; increasing the ratio of PCM mass to water mass from 10 to 100% reduced the productivity by up to 30%. While, incorporating large PCM mass in the system has kept the basin water temperature higher for longer time. This is useful if the unit is to be used for supplying potable water and hot water mainly after sunset and for heating purposes especially in cold places. Reducing the overall heat transfer coefficient from 10.4 to 2.6 $W/m^2 \cdot K$ can increase the productivity by > 100%. The cooling water through the glass cover can have significant effect (37% increase) on the unit productivity of fresh water if its flow rate is increased from 0.01 to 0.1 kg/s.

1. Introduction

Water demand is increasing worldwide, while the available potable water is diminishing due to the water sources becoming saline and/or polluted or the only available source is saline water (i.e. seawater). Nowadays, countries that were deemed to have sufficient water are forced to treat some if not most of their water supplies due to these water problems. All water treatment methods require energy either as thermal and/or electrical. In remote areas where connection to the grid is normally not available, providing potable water from salty or polluted water becomes a challenge. However, most remote areas located near the sea and lack fresh water have abundant solar irradiation, which can be utilized to supply energy to solar desalination units.

Solar distillation is one of the most important water purification processes with solar still being the most common unit used in small capacity due to its low price and easy utilization. Several types of solar stills are used such as pit, cone, and domo solar stills; however, the basin still is the most common type. Basin stills have many different variations, but the two main categories of basin stills are having single or double sloped cover [1]. Solar stills can produce several liters of water per square meter of still area per day, with a reasonable capital cost investment. The average efficiency of the solar stills ranges between 30 and 60% with a long life time [2]. The use of solar still is not so popular due to its low productivity. Many works have been undertaken to improve the productivity of these stills. The productivity is mainly affected by the solar intensity [3], the ambient temperature, the glass cover material and its thickness [4], the velocity of wind [5,6] and the depth of water in the basin [7]. The recent work by Selvaraj and Natarajan [8] and Sharshir et al. [9] summarized the factors influencing the performance of solar sill. Under optimized operating, Rajamanickam and Ragupathy [10] obtained a maximum productivity of 3.1 $L/m^2 \cdot day$ using double slope solar still, while Abu-Arab et al. [11] reported a productivity of a single basin solar still to be < 5 $L/m^2 \cdot day$. This low efficiency is mainly due to the complete loss of water latent heat of condensation on the glass cover. To improve the performance of conventional solar stills, several improvements have been made, such as attaching solar collector [12] and the use of phase change material (PCM) [13,14] to store the solar energy during the day time and release the stored energy during night, hence keeping the water warm for longer hours.

Kalbasi et al. [15] modeled single and double effect solar stills and validated the modeling results experimentally. It was found that the

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separation of condensing surface and solar energy receiving surface will increase the daily productivity by 94% compared to conventional one. They also demonstrated that water depth in the basin has negative effect on the productivity, while increasing the temperature difference between the condensing surface and water in the basin will increase the productivity.

Rai and Tiwari [16] studied the performance of a solar still coupled with a flat plate solar energy collector. The study indicated that, the daily distillate production of a coupled single basin solar still is 24% higher than that of uncoupled still. Sathyamurthy et al. [17], and Badran and Al-Tahaineh [18] also studied the effect of coupling a solar collector to the solar still and found similar enhancement in the unit productivity. Other designs have been developed that use PCM to store the solar energy during the day time and to keep the solar stills running for 24 h. Storage system could be either sensible or latent heat. The latent heat energy storage systems have many advantages over the sensible systems including a large energy storage capacity per unit volume and almost constant temperature for charging and discharging [19]. Several research works have discussed the use of PCM as energy storage system for solar stills [5,14,20–26].

Sharshir et al. [9] incorporated paraffin wax as PCM to a weir-type cascade solar still and obtained an improvement of 31% on the daily productivity compared to that without PCM. Shalaby et al. [27] also used paraffin wax as PCM with a v-corrugated absorber single-basin still enhanced and obtained an enhancement of 12% on the productivity. Mousa and Gujarathi [14] theoretically analyzed the productivity of desalination units enhanced by PCM. It was found that the presence of PCM (melting point of 40 °C) have resulted in higher basin temperature after sunrise. They also concluded that choosing a PCM with higher melting point (40 to 50 °C) have led to higher productivity.

The previous work by Mousa and Abu Arabi [12] showed that basin solar still enhanced by an external solar collector cover with cooled glass cover improved the unit productivity. Further improvement of the same unit was carried out by Al-harahsheh et al. [13] who incorporated Sodium Thiosalfate Pentahydrate as PCM. A compartment attached was added to the basin bottom containing the PCM. The PCM were placed in plastic tubes having 2 mm thickness which were immersed in distilled water. This distilled water received heat from the water basin and is then transferred and stored in the PCM.

The objective of this study is to theoretically model the unit developed by Al-harahsheh et al. [13] incorporated with Sodium Thiosulfate Pentahydrate as PCM and attached to an external solar collector. To the authors' best knowledge modeling of such combination was not studied previously. The effect of operational parameters such as the cooling water flow rate, the water circulation flow rate through the solar collector, basin water depth, and ambient conditions on the system productivity is studied.

2. System description

The solar desalination system studied theoretically in this work is shown in Fig. 1. The system consists of solar basin connected to a solar collector to provide additional solar energy. The solar collector used in this study is flat plate rectangular solar collector, model DSC 25 with a collector area of 2.5 m^2 and dimensions (2005 mm length, 1225 mm width and 90 mm m depth). A compartment containing PCM is attached to the basin from the bottom. The PCM is placed in tubes that are immersed in distilled water. The solar basin has a double glass cover with provision for cooling water to pass through. The PCM used in the experimental unit is Sodium Thiosulfate Pentahydrate (STSPH). The details of the experimental set up are described in Al-harahsheh et al. [13] work.

The operation of the system involves two processes forming a cycle; heat charging and heat discharging. In the heat charging, which occurs during the daylight time, water in the basin is heated by two means: by the directly absorbed solar energy in the basin water and by the heat received from the solar collector via a coil immersed in the water as heat exchanger. Due to the increase in water basin temperature, heat would flow to the PCM compartment causing its temperature to increase, storing sensible energy initially (when $T < T_m$) in the solid phase. As the PCM temperature reaches the melting point ($T = T_m$), it remains constant until all the PCM melts, storing latent heat. If the heat is still flowing, it causes the PCM temperature to rise above the melting point ($T > T_m$), storing sensible heat in the liquid phase. In the heat discharging process, which occurs as the sun sets, the basin water starts to cool, thus the stored energy in the PCM (sensible and latent) is released back to the water in the basin as sensible and latent heat, allowing continuous operation (day and night) of the unit.

It should be mentioned that this unit can serve as a source of fresh water as well as a source of hot water. The hot water can come from the glass cover cooling water whose temperature may reach as high as 40 °C in summer time.

3. Theoretical modeling

3.1. The solar irradiation (Q_r) and ambient temperature

To carry out the theoretical study, solar irradiation and ambient temperature are needed. The solar irradiation received by the experimental unit described above is normally represented as Q_r in (W/m^2). It varies with time reaching its peak value normally at about noon time in Jordan. Fig. 2 shows a typical solar irradiation versus daytime in Jordan. The measured data shown on the figure was recorded on May 15, 2015 as provided by the Energy Center at Jordan University of Science and Technology, which is located in the same vicinity. Matlab® Software was used to find the best fit equation representing the measured data in order to use in the modeling and simulation. The obtained equation from the Matlab software is;

$$Q_r = 864\ \exp\left[-\left(\frac{t-13.11}{4.064}\right)^2\right] \tag{1}$$

where t is solar time in (hour), and Q_r is solar irradiation in (W/m^2).

The ambient temperature data for the same day is also expressed as well by the following equation

$$T_a = 32.54\ \exp\left(-\left(\frac{t-13.4}{14.32}\right)^2\right) \tag{2}$$

Eqs. (1) and (2) are used in the modeling and simulation of the unit. The model is based on performing unsteady state energy and mass balances to estimate the basin water temperature, the PCM temperature, and the unit productivity as a function of time. The details of modeling are presented below.

3.2. Heat charging mode

Fig. 3 represents a schematic sketch of the water in the basin with PCM placed underneath. As described above, the charging mode takes place when the unit receives solar irradiation (Q_r) during the daytime hours. Accordingly, the water in the basin heats up causing evaporation. The vapor condenses on the inner surface of the glass cover. The condensate slips on the inner glass surface and is collected at the bottom.

Performing an overall energy balance around water in the basin gives:

$$m_w\frac{dH_w}{dt} = [\dot{m}_F H_F + A_P Qr + A_P Q_{ext} + \dot{m}_c H_{c,in}] - [A_P Q_L^{top} + \dot{m}_c H_{c,out} + \dot{m}_f H_f + A_P Q_{pcm}] \tag{3}$$

where:

- m_w is water mass in the basin (kg), A_P is basin's bottom area (m^2),

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